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Real-Time Control and Evaluation of a Teleoperated Miniature Arm for Single Port Laparoscopy

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***Abstract*— This paper presents the control architecture and the first performance evaluation results of a novel and highly-dexterous 18 degrees of freedom (DOF) miniature master/slave teleoperated robotic system called SPRINT (Single-Port laparoscopy bimaNual roboT). The system was evaluated in terms of positioning accuracy, repeatability, tracking error during local teleoperation and end-effector payload. Moreover, it was experimentally verified that the control architecture is real-time compliant at an operating frequency of 1 kHz and it is also reliable in terms of safety. The architecture accounts for cases when the robot is lead through singularities, and includes other safety mechanisms, such as supervision tasks and watchdog timers. Peliminary tests that were performed by surgeons *in-vitro* suggest that the SPRINT robot, along with its real-time control architecture, could become in the near future a reliable system in the field of Single Port Laparoscopy.**

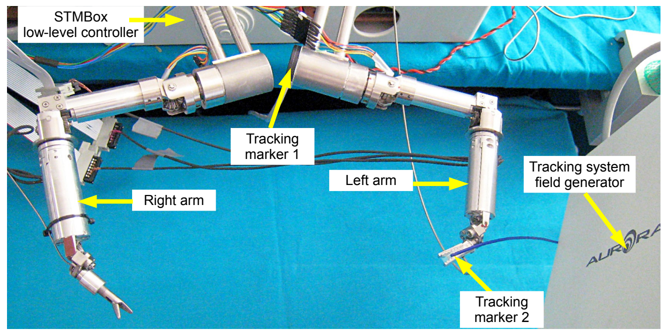

Fig. 1. Prototype of the bimanual robot for Single Port Laparoscopy.

I. Introduction

LAPAROSCOPY is a conventional surgical technique used in hospitals worldwide that offers a reduced invasiveness when compared to open surgery procedures. However, there are several technical drawbacks yet to be improved.

In pursuit of providing patients with surgical procedures leading to less postoperative trauma and better cosmetic results, and also offering surgeons more dexterity and freedom of movement, current research in minimally invasive robotic surgery focuses on: 1) reducing the number and size of incisions, and 2) increasing the number of Degrees of Freedom (DOF) available for surgery inside the patient's body. Natural orifice transluminal endoscopic surgery (NOTES), for instance, is a synthesis between endoscopy and laparoscopy aiming to offer all advantages from both methods in a scenario with no visible scars. But despite initial enthusiasm inspired by first results [1] [2], reliable closure of the viscerotomy required by this technique remains a critical step in avoiding infection of the area of interest, and a more adequate instrumentation is needed [3].

Another emerging technique, is the so-called single port laparoscopy (SPL). The fundamental idea is to perform a single umbilical incision by means of which all laparoscopic instruments are inserted [4], avoiding additional incisions and gaining access to the abdomen in a practically scar-less way from the surgical point of view. New special articulated and steerable laparoscopic instruments have been developed for this purpose [4] [5], but unfortunately a significant learning curve has to be taken into account as Neto *et al.* [5] have shown.

Since the 80's, research in surgical robotics has attracted growing interest from both academia [6] and industry [7]. In this scenario, Intuitive Surgical Inc. (Sunnyvale CA, USA) has become a leader in commercial surgical robotics with the *da Vinci* robot, which is a master/slave system providing tools with six DOF (two more than conventional laparoscopic instruments) that enables to replicate the movements of the human wrist. As a further matter Haber *et al.* [8] [9] and White *et al.* [10], have demonstrated the feasibility of using the *da Vinci* robot even for NOTES and SPL by evaluating recently developed instruments, though with considerable limitations.

In this context, miniature dexterous robots specifically designed for the most recent surgical techniques represent the next challenge in surgical robotics. Several works were presented in recent years [11] [12] [13], however, results comparable with those of the commercial *da Vinci* system still have to be demonstrated.

SPRINT (Fig. 1) is a novel and modular master/slave teleoperated robotic system for SPL, whose mechanical design and dimensional requirements are described in [14]. The system provides a total of 18 DOF completely located inside the patient's body, i.e. each arm provides 7 DOF and 4 additional DOF are provided by an external positioning platform (not shown here) specifically designed to respect the fulcrum constraint and to position the bi-manual robot with

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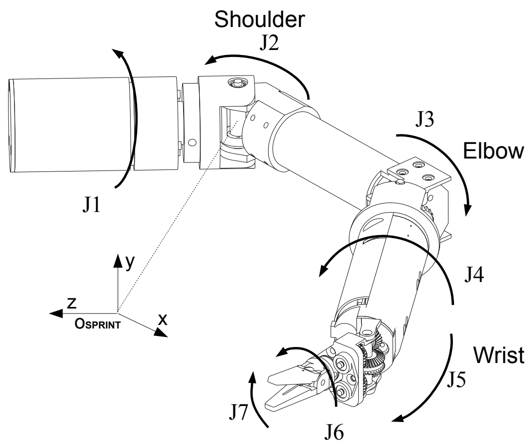

Fig. 2. Kinematic configuration of one robotic arm (O_{SPRINT} is located at the intersection of J_1 and J_2).

high accuracy by using a parallel robot architecture [15]. As a result, the system allows to reproduce with high dexterity and less invasively the surgeon's gestures at the level of the robotic end-effectors.

This paper focuses on the implemented control architecture which is fundamental to safely operate the recently developed SPRINT system. Furthermore, the first results concerning the evaluation of the system will be presented. Section II provides an overview of the system, while Section III discusses on specific details of the real-time control architecture implementation. Finally Sections IV and V illustrate the obtained results, draw the conclusions and underline future developments.

II. Overview of the System

SPRINT consists of a bi-manual slave robot with its real-time controller, and a dedicated master console. The two robotic arms of Fig. 1 will be inserted inside the abdomen of the patient through an unique cylindrical access port that has a diameter of 30 mm in conformity with the medical constraints [5]. Each robotic arm has 6 active DOF plus the gripper (Fig. 2), arranged in an anthropomorphic serial configuration designed to achieve a large workspace for performing complex surgical tasks (Fig. 3).

At the master console side, two customized Omega.7 haptic devices (Force Dimension, Nyon, Switzerland) are used, enabling to control all the 7 DOFs of each robotic arm. A first personal computer (PC) without real-time extensions is connected to the Omega device trough an USB interface. Then, at the slave side a second PC with real-time Linux based operating system communicates with the first PC for receiving the surgeon's commands. Furthermore, a low-level actuators controller, herin referred as STMBox, was developed by STMicroelectronics® using custom electronic boards. The latter has a real-time ethernet connection for communicating with the second PC that performs the high-level control tasks.

Fig. 4 synthesizes the previous hardware description and includes an Aurora electromagnetic tracker (NDI Inc., Ontario, Canada) that was not used for robot control, but only for evaluating the performance of the SPRINT system by registering the position of the base and of the end-effectors in Cartesian space, independently of the motor encoder readings. The tracking markers are visible in Fig. 1.

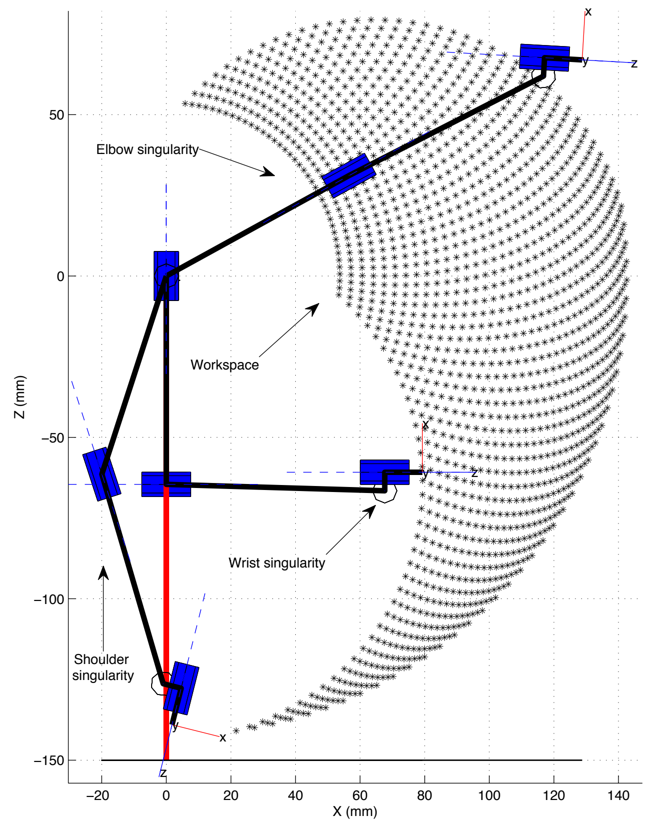

Fig. 3. Workspace of the SPRINT miniature robot: The base frame O_{SPRINT} is located at the origin (X = 0, Z = 0). Shoulder and elbow singularity configurations are not within the workspace of the robot, while wrist singularity appears whenever J5 is positioned at zero degrees.

III. Real-time Control Architecture Implementation

Hard real-time constraints must be satisfied in this type of applications for controlling the system in a deterministic and stable manner. The controller also has to account for cases in which the manipulator is lead by the surgeon through or nearby a singularity configuration, which is a typical and unpredictable situation of this type of teleoperation applications using motion increments [16]. Finally, other safeties have to be taken into account for handling situations such as system deadlocks and individual component failures.

To overcome these issues, a custom environment based on the Real Time Application Interface (RTAI) for Linux was developed. It allows to control the whole system with a rate up to 1 kHz. Multiple tasks sharing data on a shared memory space were implemented as shown in Fig. 5. The main task initializes the environment and then schedules a supervision loop that is used to verify in a round-robin

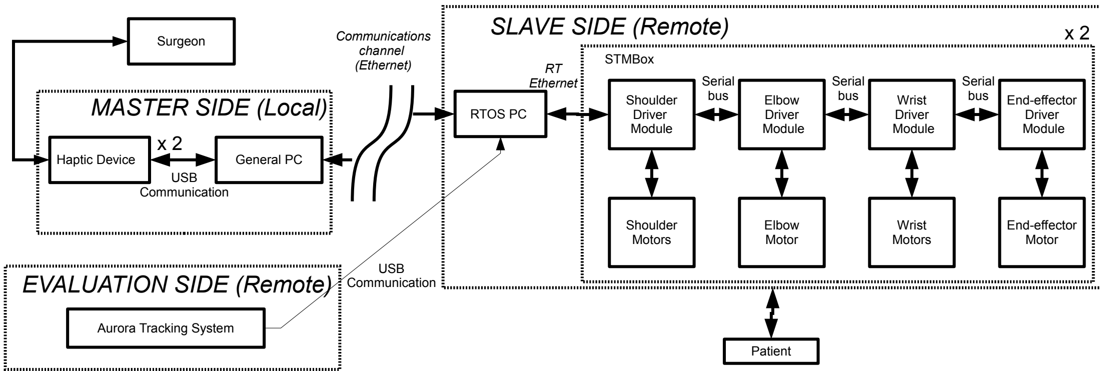

Fig. 4. Hardware system architecture

fashion the correct execution of all tasks, and also the status of the operating system through the *proc* interface. The latter is a standard Linux interface that gives useful information on the current status of RTAI (including schedulers loaded), the real-time tasks activity (priority and period) and more. The STMBox task is used to communicate with the low-level actuator controller. The teleoperation task is in charge of handling the surgeon's commands. The sensors task is used to acquire force data from a load-cell which is not yet incorporated in the arm but that was fixed externally in a table for measuring the forces that the arm can exert. As for the tasks used to perform inverse kinematics and position control loop computations, two threads are created and associated to each one of the arms, hence allowing true parallel task execution in a multi-processor environment.

All motors inside the arm are controlled by means of the STMBox driver, which is composed of four different modules: shoulder, elbow, wrist and end-effector. The modules read the position of the motors, and set the desired current or torque, thus enabling to perform in the future force control tasks (e.g. inserting a needle with an optimal constant force). They are connected in a serial manner through a bus, starting from the control board designed for the shoulder up to the end-effector modules. A real-time communication protocol called MTAP (Multi-master Tokened Access Protocol) developed by STMicroelectronics® together with the University of Bergamo, allows the transmission of data from and to all the modules at 1kHz [17]. The STMBox has been designed to include additional hardware safeties in case of system failure by implementing a communications timeout and also a deadlock watchdog timeout. In case of failure, the current of the actuators is properly handled to break the robotic arm.

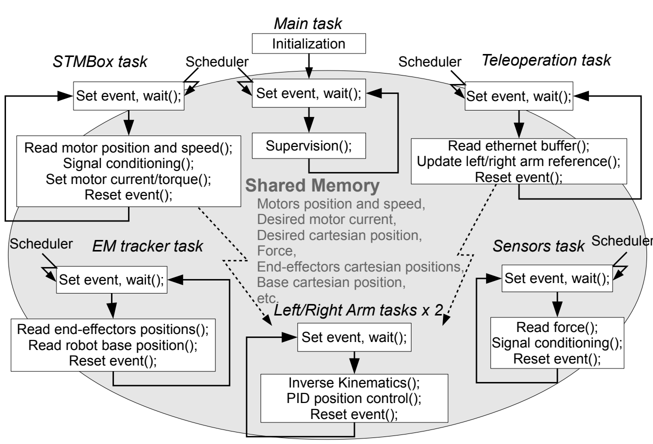

Fig. 5. Software system architecture.

The kinematic model of a single arm, following the standard Denavit-Hartenberg rules, is summarized in Table I. Fig. 3 illustrates the three different singular configurations, which are pointed using arrows. In the case of the left and right arm tasks of Fig. 5, a damped least-squares (DLS) technique [16] was used for computing the inverse kinematics in order to account for situations when the surgeon attempts to lead the robot through or nearby a singularity using motion increments obtained at the master console. Additionally, since the kinematic configuration of the current embodiment may vary in the future, the DLS technique offers the advantage that it can be easily re-used with minor parameter adjustments before a final version of the arm is available. However, if an analytical solution still exists for the next arm versions, it will be preferred over the DLS technique.

All computations are performed using the dual quaternion motion representation, instead of using the traditional pairs of translation and Euler angles, or replacing the latter by quaternions. This is due to the many advantages associated with this singularity free representation, particularily well adapted for real-time implementations [18] [19]. For instance, using this approach the position and orientation errors are calculated in a single step [18]. This is the same case for defining motion increments from the haptic interface (requiring a single dual quaternion multiplication for defining the relative motion), and for updating the desired cartesian reference (requiring a single operation known as decompositional multiplication) [19]. Finally, the representation of bi-manual manipulation tasks is also simplified by using a cooperative dual-task space framework [20].

As for the computation of the required motor currents once the desired joint positions are obtained from the inverse kinematics, a Proportional-Integral-Derivative (PID) local controller with velocity and friction feed-forward terms was implemented [21]. As usual, the velocity feed-forward is

TABLE I
DENAVIT-HARTENBERG PARAMETERS OF A SINGLE SPRINT ARM

Link	a_i (link length)	a_i (link twist)	d_i (link offset)	θ_i (joint angle)
1	0	$\pi/2$	0	ϑ_1
2	a_2	0	0	ϑ_2
3	0	$\pi/2$	0	ϑ_3
4	a_4	$-\pi/2$	d_4	ϑ_4
5	a_5	$\pi/2$	0	ϑ_5
6	0	0	d_6	ϑ_6

computed using the current and next desired targets. For the friction feed-forward term, a simple determination of friction is used by considering that it could be present if the process variable has not changed (i.e. multiple-points derivative of the position error) and the desired target for the next iteration is not null. The average value of the current required to move each joint when the motor is initially stopped was experimentally determined.

IV. EVALUATION OF THE SYSTEM: SETUP AND RESULTS

Measurements reported in literature [22] [23] and performances of other teleoperated systems for surgery [24], [25] have been taken into account in order to evaluate the SPRINT.

A. Positioning accuracy and precision

For this purpose the arm was controlled to draw autonomously different shapes. An example in which the corners of a cube with 2 cm sides were used as cartesian reference for the arm, is show in Fig. 6. The cartesian speed was set to 0.5 cm/s, and the point $(0,0,0)$ corresponds to the home position of the end-effector. During each cycle, the shapes were designed 15 times. Accuracy and precision measurements were performed using the positions of the end-effector w.r.t. the arm's base, that were collected using the external tracking system. Considering the root mean square registration error, an accuracy ± 5 mm was observed. Finally, concerning the combined variance of the point sets, a precision of ± 1 mm was determined. These results are satisfactory considering the current prototyping phase of the arm. The accuracy will be improved in next versions [14].

B. Tracking error during teleoperation

The SPRINT was teleoperated by hand for simulating the normal use of the system during surgery. The transmitted data between the master console and the slave PC was timestamped in order to obtain the plot shown in Fig. 7. It depicts the RMS error between the three-dimensional cartesian positions commanded at the master side and the measured positions of the end-effector recorded with the external tracking system, exclusively used for validation. An average error of 5 mm was observed in accordance with the measured accuracy. Results will be further improved by future works on the communications channel, as well as through the implementation of more advanced controllers for the whole system.

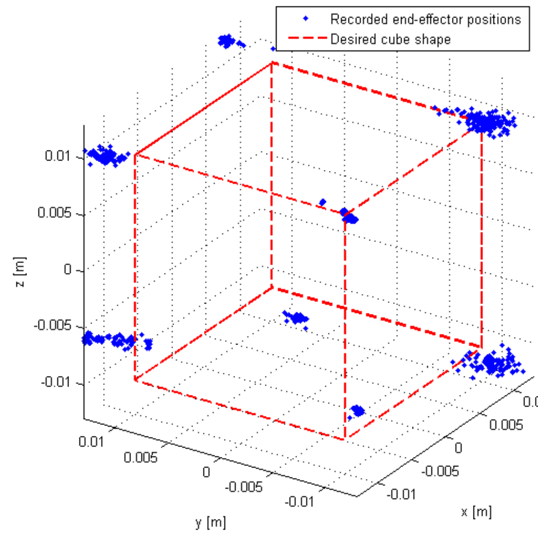

Fig. 6. Cube test example: the point-clouds should correspond with the corners of the cube (intermediate trajectory points not corresponding to the corners are not shown).

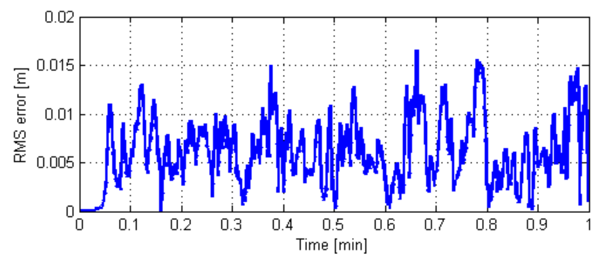

Fig. 7. Root mean square position tracking error during local teleoperation.

C. Force measurements

In surgery, retraction of organs and tissues, represents one of the most common operations done by surgeons during interventions. In order to simulate this kind of tasks, tests have been performed by pulling with the end-effector a rigid cantilever linked to an ATI nano17 force transducer, also rigidly fixed. The experiments were performed during teleoperation (i.e. by manually controlling the arm using the haptic interface). It was observed that SPRINT reaches forces of 5 N in retraction as targeted in [14], and also complying with the medical requirements defined by medical experts.

D. Real-time compliance

Execution overruns were recorded during the tests. It was observed that during 99.9 % of the time there were no execution overruns when operating at 1 kHz.

V. CONCLUSIONS AND FUTURE WORKS

The first evaluation results for the current prototype of a novel manipulator for SPL were presented. It was confirmed that the system satisfies the design specifications [14]. Given the prototyping stage, observed results were considered satisfactory. It is expected that the system will be ready in the very near future for performing *ex-vivo* and *in-vivo* tests on animal specimens for a more extensive validation.

Mechanical improvements in the transmission of the first two proximal joints will be perfomed in the second prototype in order to reduce backlash. In particular, the bevel gears currently used in the first two joints will be substituted with a linkage. The remaining mechanical limitations (i.e. backlash and joint flexibility) will also be tackled through the implementation of more advanced controllers, such as anti-backlash or adaptive controllers. Moreover, cooperative control methods will be implemented based on the cooperative dual-task space framework to enhance the bi-manual manipulation capabilities of the robotic system.

VI. ACKNOWLEDGMENTS

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REFERENCES

[1] A. N. Kalloo, V. K. Singh, S. B. Jagannath, H. Niiyama, S. L. Hill, C. A. Vaughn, C. A. Magee, and S. V. Kantsevoy, "Flexible transgastric peritoneoscopy: a novel approach to diagnostic and therapeutic interventions in the peritoneal cavity." *Gastrointestinal Endoscopy*, vol. 60, no. 1, pp. 114–117, Jul. 2004.

[2] S. B. Jagannath, S. V. Kantsevoy, C. A. Vaughn, S. S. Chung, P. B. Cotton, C. J. Gostout, R. H. Hawes, P. J. Pasricha, D. G. Scorpio, C. A. Magee, L. J. Pipitone, and A. N. Kalloo, "Peroral transgastric endoscopic ligation of fallopian tubes with long-term survival in a porcine model," *Gastrointestinal Endoscopy*, vol. 61, no. 3, pp. 449–453, Mar. 2005.

[3] A. Lehman, J. Dumpert, N. Wood, L. Redden, A. Visty, S. Farritor, B. Varnell, and D. Oleynikov, "Natural orifice cholecystectomy using a miniature robot," *Surgical Endoscopy*, vol. 23, no. 2, pp. 260–266, Feb. 2009.

[4] J. Romanelli and D. Earle, "Single-port laparoscopic surgery: an overview," *Surgical Endoscopy*, vol. 23, no. 7, pp. 1419–1427, Jul. 2009.

[5] M. Galvao Neto, A. Ramos, and J. Campos, "Single port laparoscopic access surgery," *Techniques in Gastrointestinal Endoscopy*, vol. 11, no. 2, pp. 84–93, Apr. 2009.

[6] J. S. Dai, "Surgical robotics and its development and progress," *Robotica*, vol. 28, no. 2, p. 161, Mar. 2010.

[7] P. Gomes, "Surgical robotics: Reviewing the past, analysing the present, imagining the future," *Robotics and Computer-Integrated Manufacturing*, vol. 27, no. 2, pp. 261–266, Apr. 2011.

[8] G.-P. Haber, S. Crouzet, K. Kamoi, A. Berger, M. Aron, R. Goel, D. Canes, M. Desai, I. S. Gill, and J. H. Kaouk, "Robotic notes (natural orifice translumenal endoscopic surgery) in reconstructive urology: Initial laboratory experience," *Urology*, vol. 71, no. 6, pp. 996–1000, June 2008.

[9] G.-P. Haber, M. A. White, R. Autorino, P. F. Escobar, M. D. Kroh, S. Chalikonda, R. Khanna, S. Forest, B. Yang, F. Altunrende, R. J. Stein, and J. H. Kaouk, "Novel robotic da vinci instruments for laparoendoscopic single-site surgery," *Urology*, vol. 76, no. 6, pp. 1279–1282, Dec. 2010.

[10] W. M. White, G.-P. Haber, R. K. Goel, S. Crouzet, R. J. Stein, and J. H. Kaouk, "Single-port urological surgery: Single-center experience with the first 100 cases," *Urology*, vol. 74, no. 4, pp. 801–804, Oct. 2009.

[11] D. Canes, A. C. Lehman, S. M. Farritor, D. Oleynikov, and M. M. Desai, "The future of notes instrumentation: Flexible robotics and in vivo minirobots," *Journal of Endourology*, vol. 23, no. 5, pp. 787–792, May 2009.

[12] W. M. White, G.-P. Haber, and J. H. Kaouk, "Robotic single-site surgery," *Current Opinion in Urology*, vol. 20, no. 1, pp. 86–91, Jan. 2010.

[13] K. Xu, R. Goldman, J. Ding, P. Allen, D. Fowler, and N. Simaan, "System design of an insertable robotic effector platform for single port access (spa) surgery," *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 5546–5552, Oct. 2009.

[14] M. Piccigallo, U. Scarfogliero, C. Quaglia, G. Petroni, P. Valdastri, A. Menciassi, and P. Dario, "Design of a novel bimanual robotic system for single port laparoscopy," in *IEEE/ASME Transactions on Mechatronics, focus section on surgical and interventional medical devices*, vol. 15, no. 6, Dec. 2010.

[15] R. Beira, L. Santos-Carreras, G. Rognini, H. Bleuler, and R. Clavel, "Dionis: A novel remote-center-of-motion parallel manipulator for minimally invasive surgery," in *Applied Bionics and Biomechanics, special issue in surgical robotics*, 2010, to be published.

[16] S. Chiaverini, B. Siciliano, and O. Egeland, "Review of the damped least-squares inverse kinematics with experiments on an industrial robot manipulator," *IEEE Transactions on Control Systems Technology*, vol. 2, no. 2, pp. 123–134, June 1994.

[17] D. Caltabiano, D. Brugali, R. Sannino, D. Ghezzi, and L. Spelgatti, "A real-time communication protocol for interconnecting robotic smart devices," *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1896–1901, Sept. 2008.

[18] H.-L. Pham, V. Perdereau, B. Adorno, and P. Fraisse, "Position and orientation control of robot manipulators using dual quaternion feedback," *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 658–663, Oct. 2010.

[19] B. Adorno, A. B, P. Fraisse, and P. Poignet, "Towards a cooperative framework for interactive manipulation involving a human and a humanoid," *IEEE Internation Conference on Robotics and Automation*, 2011.

[20] B. Adorno, P. Fraisse, and S. Druon, "Dual position control strategies using the cooperative dual task-space framework," *IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 3955–3960, Oct. 2010.

[21] R. Heathfield, L. Kirby, J. Klein, *et al.*, *C Unleashed*. Sams Publishing, 2000, ch. 18.

[22] J. D. Brown, J. Rosen, L. Chang, M. Sinanan, and B. Hannaford, "Quantifying surgeon grasping mechanics in laparoscopy using the blue dragon system," *Medicine Meets Virtual Reality*, vol. 13, pp. 34–36, 2004.

[23] C. Richards, J. Rosen, B. Hannaford, C. Pellegrini, and M. Sinanan, "Skills evaluation in minimally invasive surgery using force/torque signatures," *Surgical Endoscopy*, vol. 14, pp. 791–798, Sep. 2000.

[24] A. Madhani, "Design of teleoperated surgical instruments for minimally invasive surgery," Ph.D. dissertation, Massachussets Institute Of Technology, 1998.

[25] M. Cavusoglu, "Telesurgery and surgical simulation: Design, modeling, and evaluation of haptic interfaces to real and virtual surgical environments," Ph.D. dissertation, University of California, Berkeley, 2000.